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APPLICATION OF THE PEGASUS II PULSED-POWER FACILITY TO THE STUDY OF INERTIAL INSTABILITY AND FRACTURE OF CYLINDRICAL TUBES OF SOLID ALUMINUM*

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Abstract

Understanding the surface stability of metals undergoing dynamic fracture at shock breakout is important to several applications in metals processing. The advantages of using the Pegasus II facility to investigate the phenomena occurring at shock break out are described. As an example of the data collected, we concentrate on brief descriptions of two experiments that compared the tensile failure, i.e. "spall", patterns in the presence of sinusoidal perturbations seeded on the free inner surface of cylindrical samples of 3 types of Al. These samples were composed variously of soft Al 1100-O, structural grade Al 6061-T6, and ultra-pure 99.99% Al and were subjected to Taylor waves with shock pressures of 14 GPa. We show that the material behind the exiting surface undergoes a type of failure termed here "microspall", resulting in the production of a significant volume of low-density, probably granular, material. The failure mechanism, combined with the forces that cause inertial instability, leads to rapid pattern growth in the failed material and subsequent pattern growth on the surface. Pattern growth was studied as a function of perturbation wavelength and amplitude. The different Al samples vary by an order of magnitude in yield strength, and some increase in pattern instability was observed at lower yield strength. The ultra-pure Al has exceptionally large grain size, in the mm range. No appreciable variation of spall pattern was observed due to grain size.

I. PEGASUS II FACILITY

Understanding the surface stability of metals undergoing dynamic fracture at shock breakout is important to applications in metals processing including explosive hardening and forming, impact cratering, and the development of impact-resistant materials. In the last two years, we have conducted a series of experiments on the Pegasus II microsecond z-pinch facility at Los Alamos National Laboratory. The goal of these experiments was to study instabilities generated at the surface of metals by the break out of high-pressure shocks. The Pegasus II facility is excellent for this type of experiment because it can produce a cylindrically-convergent shock wave which, by its nature, has no "edge effects" and which has less than 1% azimuthal variation. In addition, the pressure is highly reproducible and easily varied within a range of 14-50 GPa without reconfiguration of the apparatus. The cylindrical geometry and EM drive allow for an extensive diagnostics suite to report the current delivered to drive the liner, the collision time, and the subsequent behavior of the target. The diagnostics include 3-5 axial x-ray images for each shot, up to 5 radial images, laser backlighting, and optical cameras to record the self-emission of the gas fill. Each of these diagnostics can be timed independently. A detailed diagram of the diagnostics suite is available in an earlier report.[1] A sketch of the target appears in Fig. 1.

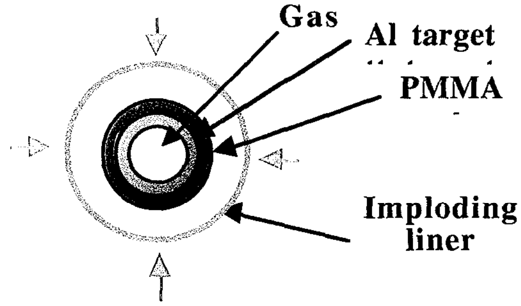

Figure 1. The cross-section of a typical target. An aluminum cylinder of 3-mm thickness is surrounded by 2 mm of plastic and gas-filled with 1 atm of Xe or Ar. The imploding liner of the z-pinch, made of .4 mm thick Al collides with the target at 1.5 km/sec. Various perturbations are inscribed on the inside surface of the Al target.

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II. TWO EXPERIMENTS

As an example of the data our team has produced on this machine, let us look at the results of two experiments designed to study the spall patterns and instabilities that grow on cylinders comprised of different types of aluminum at 14 GPa. The static axial images of the targets are shown in Figs. 2a and 3a. The experiment in Fig. 2 was composed of a cylinder of Al 6061-T6 of height 17.5 mm, i.d. 20 mm, and thickness 3 mm. The target was encased in a 2 mm Lucite (PMMA) holder, and was filled with 1 atm of Xe gas. The purpose of the Xe gas is to monitor the passage of the shock, both in axial x-ray images which capture the increased Xe density at shock passage, and by recording the self-emission of the shocked Xe by optical cameras. The Lucite holder shapes the shock into a Taylor wave; without this holder, the shock would have a square-wave shape. Inscribed parallel to the axis of symmetry on the inner surface were 13 wavelengths of 8 degree (1.396 mm) wavelength, 60 μm amplitude sinusoids and 9 wavelengths of 8 degree wavelength, 120 μm amplitude sinusoids. Markers were placed to indicate the original phase by marking the angle where one of each of these wavelengths protruded into the gas in the static setup.

Figure 2b shows the radiograph taken at 3.38 μs after the liner collides with the Lucite holder. The shock wave is clearly visible in the Xe gas. In the aluminum, two broad bands of low-density "micro-spalled" material have appeared, separated by a stripe of high density material. On the inner surface of the aluminum cylinder, there is a high-density "crust". Instabilities have grown in regions adjacent to both the inscribed patterns. In the region where the 120 μm perturbations were inscribed, the pattern has disrupted the crust, and material is clearly visible extending inside the radius of the crust and up to the edge of the shock in the Xe. The phase of the perturbation in this area has also inverted and now the marker points to a region that points away from center. We conclude that the 120 μm-perturbations region is "unstable" and that the 60 μm region is "stable". Nevertheless, the 60 μm perturbations have generated very significant density perturbations within the aluminum, and "stable" is not an adequate description of the degree of pattern formation.

By comparing Fig. 2a and 3a, we see that the geometry is mostly unchanged. However, the experiment of Fig. 3 contains shorter perturbations of 6 degree wavelength, 60 μm amplitude in addition to the perturbations of 8 degree wavelength present in the experiment of Fig. 2. Also, the materials present in the experiment of Fig. 3 are different. The primary purpose of the experiment of Fig. 3 was to see whether a yield strength 7 to 8 times smaller, as in Al 1100-O, would affect the stability of the perturbations. Yield strength plays a significant role in determining the growth of interfacial instabilities, such as Richtmeyer-Meshkov and Rayleigh-Taylor instabilities. An issue that has been the subject of experiments in other geometries is the effect of grain size and impurities on spall strength[2] To test the sensitivity of the microspall pattern to grain size we substituted a segment of ultra-pure 99.99% Al. The grain size of this material is several mm's in longitudinal length by .5 mm or more in cross-sectional diameter, i.e. enormous. Another difference between the two experiments is the use of 1 atm Ar as the gas fill. While Ar does not allow x-ray imaging of the shock wave in the gas, it allows discrimination between low-density Al and compressed gas in the dynamic images.

Table 1. Yield strengths of aluminum samples

	Al 6061-T6	Al 1100-O	99.9% Al
Yield strength[3] (GPa)	.29	.04	.02 (estimated)

The image in Fig. 3b, taken at 3.66 μs after collision, shows that the 120 μm perturbations are unstable in Al 1100 as in Al 6061-T6; however in this experiment we can see the Al extending significantly further into the gas. The x-ray density of the material between these fingers is similar to the density of the Ar. The 60 μm, 8 degree perturbations have a thinner crust than in the experiment with Al 6061-T6 and the perturbations appear to be emerging into the gas. The 60 μm, 6 degree perturbations clearly have matter preceding the crust. Finally, no major change in the failure patterns, either in density or position of the rings, is observed. There is an increase in variation from "circular" that hasn't been observed in other experiments. This roughness may reflect morphology such as larger pieces of fractured material.

This experiment was done recently, and we have not yet analyzed the radii of the rings in experiment of Figure 3 to see whether there is an appreciable difference in their position from what was observed in Al 6061.

III. SUMMARY

The Pegasus II facility has enabled the study of material failure and instability at shock breakout. We have observed microspall in various Al samples at shock breakout and explored the stability of the spalled material. This failure mode is associated with the Taylor-wave shock shape. Pattern growth in this material can be seeded by small-amplitude perturbations on the inner surface of the Al. The growth rate has been shown in these two experiments to be dependent on amplitude and to be affected modestly by yield strength. Other experiments have confirmed that the pattern growth rate depends on wavelength and on shock pressure, as well.

IV. REFERENCES

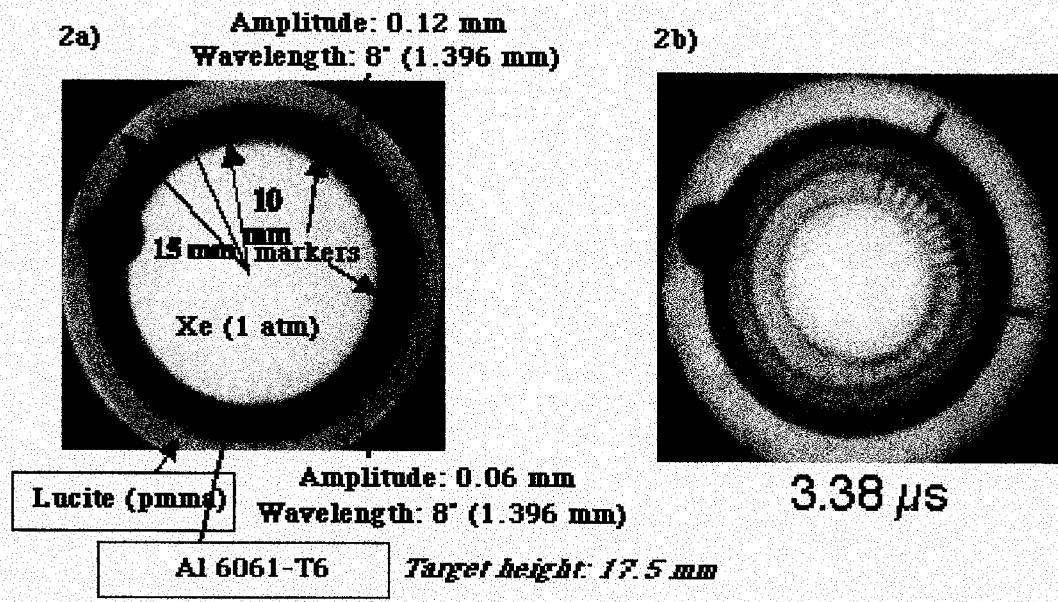
[1] E.A. Chandler, et al., "Use of the Pegasus Z-Pinch Machine to Study Inertial Instabilities in Al: A preliminary reoport" in *Proc. of the 6th International Workshop on the Physics of Compressible Turbulent Mixing,* G. Jourdan and L. Houas, eds., Marseille, Impremerie Caractere, 1997, p.111.

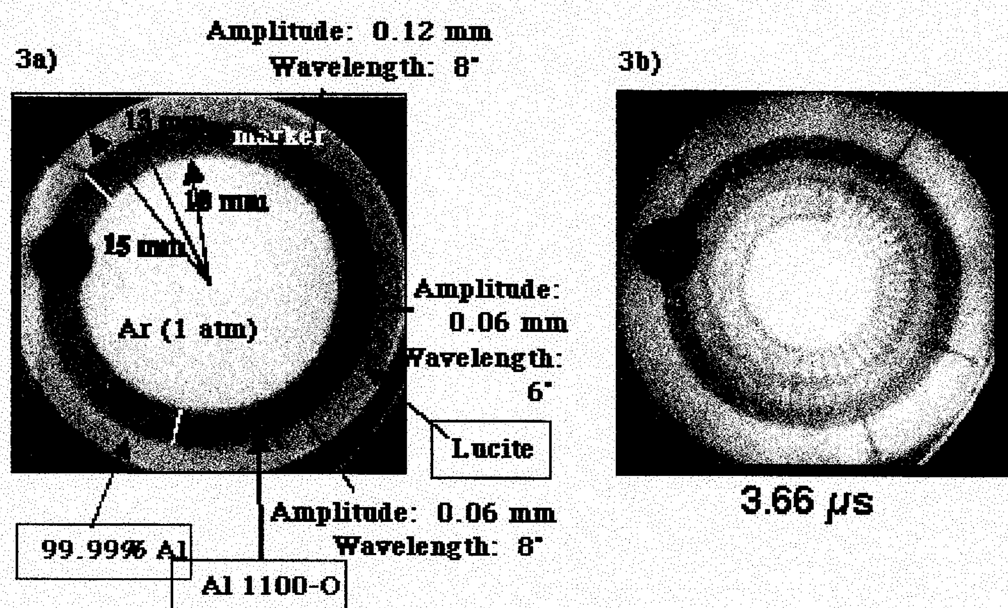
[2] M. A. Meyers, *Dynamic Behavior of Materials,* New York: J. Wiley & Sons, 1994.

[3] D. J. Steinberg, "Equation of State and Strength Properties of Selected Materials", Lawrence Livermore National Laboratory, Livermore, CA, Tech. Rep. UCRL-MA-106439, 1996.

Figure 2. *a) The* static initial image of a target made of Al 6061-T6 with Xe gas fill, and Lucite holder. On the right side of the inner surface are inscribed sinusoidal perturbations with 8 degree wavelength and .12 mm and .06 mm amplitude. *b)* The image taken at 3.38 μs after collision of the liner with the target. The shock wave front has traversed the Al, causing two bands of low-density spalled Al, and now is in the Xe gas fill. The growth of the perturbations is clearly visible.

Figure 3. *a)* The static initial image of a target made of Al 1100-O with a wedge of 99.99% Al. The gas fill is Ar. Sinusoidal perturbations of .12 and .06 mm with wavelength 8 degrees, and .06 mm with wavelength 6 degree are inscribed on the inner Al 1100-O surface. *b)* The image taken at 3.66 μs after liner collision. The growth of the perturbations is clear, with Al streaming into the gas for the larger-amplitude seeded perturbations. Also, there is some material ahead of the crust for the shorter wavelengths. The 99.99% Al shows some irregularity, but no appreciable difference in density or position of spall.


2a)
Amplitude: 0.12 mm
Wavelength: 8° (1.396 mm)
10 mm
15 mm
markers
Xe (1 atm)
Lucite (pmma)
Amplitude: 0.06 mm
Wavelength: 8° (1.396 mm)
Al 6061-T6
Target height: 17.5 mm
2b)
3.38 μs


3a)
Amplitude: 0.12 mm
Wavelength: 8°
marker
10 mm
15 mm
Ar (1 atm)
Amplitude:
0.06 mm
Wavelength:
6°
Lucite
Amplitude: 0.06 mm
Wavelength: 8°
99.99% Al
Al 1100-O
3b)
3.66 μs